183. PHYSICAL PROPERTIES OF TUFFS OF THE OAK SPRING FORMATION, NEVADA

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Work done in cooperation with the U.S. Atomic Energy Commission

The U.S. Geological Survey has made intensive physical properties studies in support of the Atomic Energy Commission's underground weapons test program at the Nevada Test Site. Most of the underground nuclear explosions in the 1 to 20 kiloton range have been detonated in the tuffs of the Oak Spring formation of Tertiary age. The underground test area is located in a mesa at the northwest corner of the Nevada Test Site, approximately 55 miles north of Mercury, Nev.

Near the test chambers, the tuffs are about 2,000 feet thick. All are rhyolitic to quartz latitic in composition (Wilcox, 1959). The tuffs may be subdivided into three groups on the basis of texture: bedded tuff, friable tuff, and welded tuff. The bedded tuffs are distinguishable from the friable tuffs by their greater coherency. The chemical difference between bedded and friable tuffs is small, except for a greater content of water in the bedded tuffs. In the friable tuffs, the conversion of glass fragments to zeolite is not so extensive as in the bedded tuffs, and only a thin rind of zeolite surrounds the glass fragments, so the rock is only weakly cemented and crumbles readily. The welded tuffs do not differ from the other units significantly in bulk chemical composition, and generally the lower parts of welded units grade into bedded and friable tuff.

Samples for testing were obtained from several core holes drilled near the test chambers and from underground workings. Properties studied included textural properties, such as porosity, density, permeability and water content; strength and elastic properties, including acoustic velocities; thermal properties, including conductivity, enthalpy and entropy; and electrical properties.

TABLE 183.1.—*Summary of physical properties of volcanic tuffs from the Oak Spring formation*

Textural subdivision	Porosity [1] (g per cm³)	Bulk density dry [1] (g per cm³)	Grain or powder density (g per cm³)	Permeability water [2] (millidarcys)		Permeability air [2] (millidarcys)	
				Average	Range	Average	Range
Bedded tuffs	0.388±0.070	1.50±0.16	2.44±0.11	0.040	0.00076–17	0.90	0.07–39
Bedded tuffs (pumiceous)	.402± .126	1.37±0.30	2.28±0.12	11.5	3.7–61	21	4.1–75
Friable tuffs	.355± .138	1.50±0.35	2.33±0.24	1.4	0.084–27	6.0	0.95–41
Welded tuffs	.141± .089	2.18±0.23	2.55±0.09	.33	0.00092–58	0.66	0.022–58

[1] Ranges expressed are one standard deviation.
[2] Ranges expressed are the complete range of observed values.

See note below

TEXTURAL PROPERTIES

The porosities, densities and permeabilities measured on drill cores from the tuffs in the Oak Spring are summarized in table 183.1. Porosities were determined by measuring the volume of water required to saturate samples, so the values presented in table 183.1 represent interconnected pore volumes. Grain density measurements indicate that there is almost no "blind" or unsaturable porosity in the tuff.

The porosities are very high. Many hundreds of water-content determinations have been made on samples obtained in their natural state from the mine workings, and in almost every determination the rocks have been found to be almost completely saturated with water. Almost complete saturation with water is found in rocks several hundred feet above the permanent water table. The water is held by impermeable beds in perched water tables and by capillarity in fine pores in rock.

STRENGTH AND ELASTIC PROPERTIES

Tensile and compressive strengths were determined for several samples of bedded and welded tuffs at the Geological Survey laboratory, and by the Applied Physics Laboratory of the U.S. Bureau of Mines (Robertson, 1959). No samples of friable tuff were obtained for strength tests, because the strength was too low to permit coring of a long enough specimen. Average uniaxial tensile and compressive strengths under atmospheric confining pressure, are listed in table 183.2.

Values of compressive strength are about 25,000 pounds per square inch (psi) for the welded tuff and about 5,000 psi for the bedded tuff. As might be expected, the compressive strengths of both types of tuff are much higher than the tensile strengths. The tensile strength, under atmospheric confining pressure, is about 500 psi for welded tuff and about 200 psi for bedded tuff.

Elastic moduli given in table 183.2 were determined by the Bureau of Mines by measuring the resonant frequencies of 2-inch samples excited in longitudinal and torsional modes, and also from the slope of the stress-strain curves obtained during static load tests.

Shear and dilatational velocities given in table 183.2 were measured in small samples of tuff using an ultrasonic pulse technique at a frequency of 400 kilocycles per second (Peselnick, 1959). Dilatational velocities were also measured at confining pressures up to 450 psi and it was found that velocity of acoustic waves was increased 50 to 100 percent over the value at atmospheric confining pressure for friable tuffs, 10 to 20 percent for bedded tuffs, and not appreciably in welded samples.

A great amount of information was obtained concerning acoustic velocities in place by refraction seismic surveys in drill holes and in tunnels and by acoustic logging of drill holes. It is likely that the acoustic velocity of rock in place is determined to a large extent by fracturing in the rock and by the confining pressure. This is particularly well shown by the acoustic log in the right column of figure 183.1. A linear increase in velocity with depth is apparent, probably representing the effect of increasing overburden pressure. The rock between depths of 1,050 and 1,120 feet through which an exceptionally low velocity is recorded is welded tuff, which the laboratory measurements showed to haye a high inherent velocity. The low recorded velocity is apparently caused by dry fractures.

THERMAL PROPERTIES

The enthalpy, or heat required to melt the tuff of the Oak Spring formation and to raise the liquid to a temperature of 1,500°C, given in table 183.3, was calculated from modal analyses by F. C. Kracek (1959) of the Geological Survey. Variations in total enthalpy depend on the mineral composition, particularly the amount of water in the rock, because water absorbs the highest amount of energy per unit mass.

Thermal conductivities were measured at room temperatures on several hundred drill cores of tuff. The conventional divided-bar technique was used. Measurements were made both with the samples dry and saturated with water. The data (fig. 183.2) may be

Convert permeability (millidarcy) to hydraulic conductivity?
1 darcy is equivalent to 0.831 m/day
Therefore, 1 millidarcy is about 8.3E-4 m/d.

TABLE 183.2.—*Summary of strengths and elastic properties for tuff of the Oak Spring formation*

[All measurements were made on dry samples. Velocity data for tuff in its natural state are best obtained from velocity logs (fig. 183.1).]

Test	Bedded tuff (psi)		Welded tuff (psi)	
	Avg.	Range	Avg.	Range
Uniaxial strength tests				
Tensile	120	85–165	330	165–480
Compressive	4.9×10^3	3.4–8.7	21.1×10^3	6.8–29.1
Dynamic tests				
Young's modulus	0.61×10^6	0.40–1.07	1.48×10^6	1.22–2.01
Rigidity modulus	0.30×10^6	0.20–0.49	0.59×10^6	0.40–0.77
Poisson's ratio	----------	0.06–0.09	----------	0.02–0.53
Static tension tests				
Young's modulus	0.71×10^6	0.40–1.60	1.69×10^6	0.86–1.75
Rigidity modulus	0.25×10^6	0.19–0.32	0.78×10^6	0.40–0.82
Poisson's ratio	0.03	0.02–0.04	0.08	0.05–0.15

Acoustic velocities

Test	Bedded tuff (fps)		Friable tuff (fps)		Welded tuff (fps)	
	Avg.	Range	Avg.	Range	Avg.	Range
Dilatational	5700	2750–10,500	5690	3250–8750	9750	9100–11,000
Shear	3300	2000–6200	2900	1700–5500	6360	5600–7150

TABLE 183.3.—*Modes and calculated enthalpy for tuff of the Oak Spring formation*

Constituent	Welded tuff		Bedded tuff	
	Percentage by weight	Enthalpy contribution (cal per g of rock)	Percentage by weight	Enthalpy contribution (cal per g of rock)
Quartz	35	141.9	19	77.0
Orthoclase	23	111.9	10	48.6
Albite	25	119.3	10	47.6
Anorthite	3	15.0	2	10.0
Zeolite	------	------	25	146.0
Montmorillonite	5	38.0	9	68.4
Nontronite	------	------	1	6.5
Micas	------	------	1	5.8
Magnetite	1	2.5	1	2.5
Water	8	115.0	20	288.0
Total	------	543.6	------	705.4

extrapolated to zero porosity to obtain an estimate of the conductivity of the mineral grains. Extrapolating the curve for measurements on dry samples gives a thermal conductivity of 2.67 cgs units, and for wet samples, 3.09 cgs units. The extrapolated value for dry samples is probably low because of the effects of boundaries between grains. Such boundary resistances should be less in wet samples. The thermal conductivity may be expressed in terms of porosity by an empirical equation:

$$\sigma_d=2.67(1-\phi)^{1.84} \quad (1)$$

$$\sigma_w=3.09(1-\phi)^{1.84}+\frac{0.088}{(1-\phi)4.8} \quad (2)$$

where σ_d and σ_w are the dry and wet conductivities, respectively, in millicalories per centimeter second degree, and ϕ is the pore fraction.

ELECTRICAL PROPERTIES

The electrical properties of the tuff in the Oak Spring formation were studied to determine water content of the rock in place. Direct determinations of water content are difficult because drilling water may contaminate drill-core samples, and tunnel-wall samples may be dried by circulating air. Water content may be estimated from electrical resistivity measurements, if the ground water resistivity is known. Measurements of electrical properties consisted of two types; in-place measurement of resistivities in drill holes and tunnels,

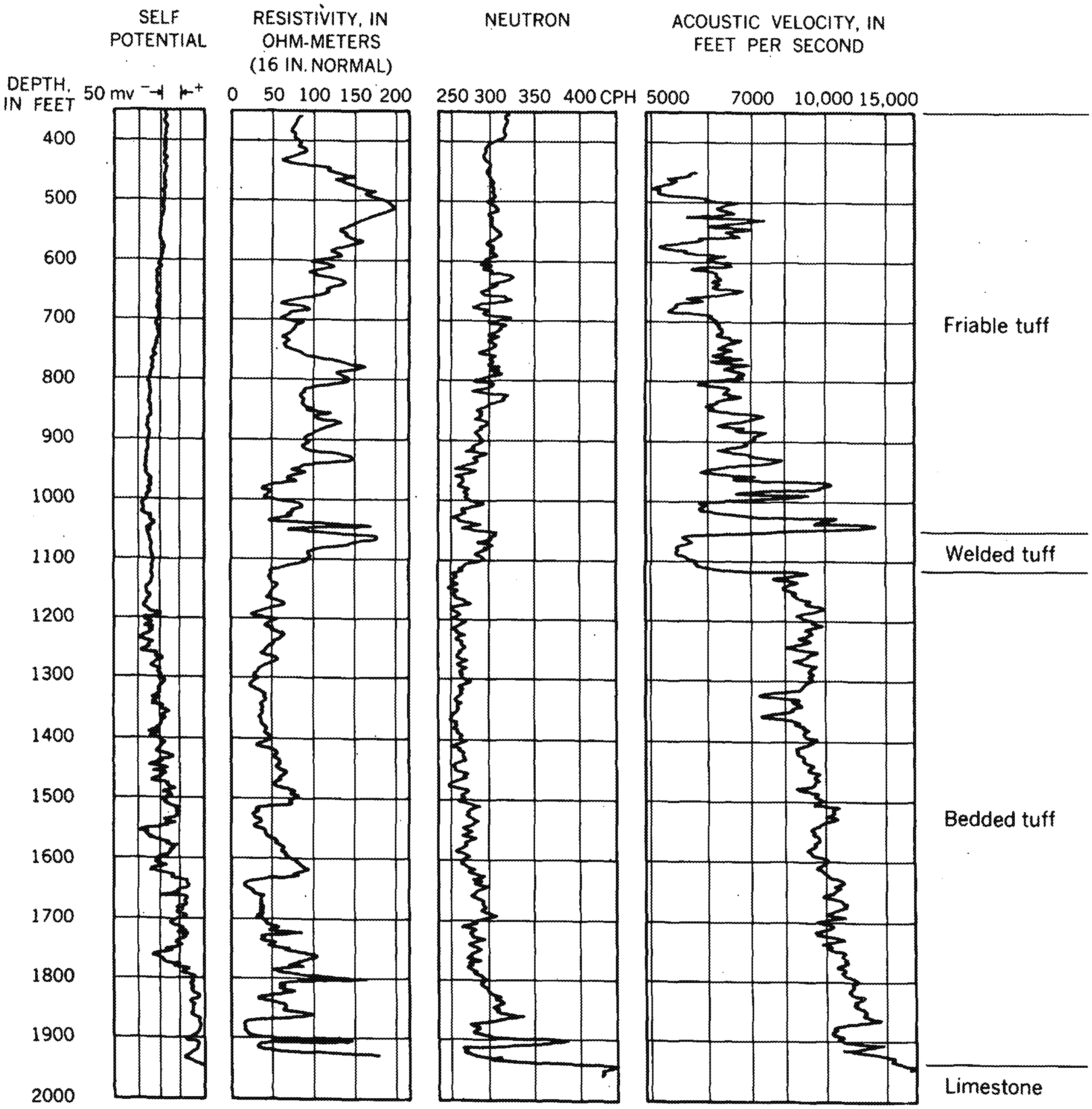

FIGURE 183.1.—Electric, neutron, and acoustic velocity logs of the Oak Spring formation in a drill hole near the underground test chamber.

and laboratory studies of the correlation between water content and electrical properties.

Resistivity measurements were made by routine methods on core samples resaturated in the laboratory with salt solutions of known concentrations (fig. 183.3). The relationship may be represented by an empirical equation:

$$\rho = 1.5\rho_w W^{-2.2} \qquad (3)$$

where ρ is the resistivity of the rock, in ohm-meters, ρ_w is the resistivity of the water saturating the rock and W is the volume fraction of water in the rock.

Rock resistivities were measured for about 100 samples of tuff obtained in the natural state by underground air drilling. These data were used with equation 3 to determine the resistivity of the pore water in the rock. The average value so determined was 1.6

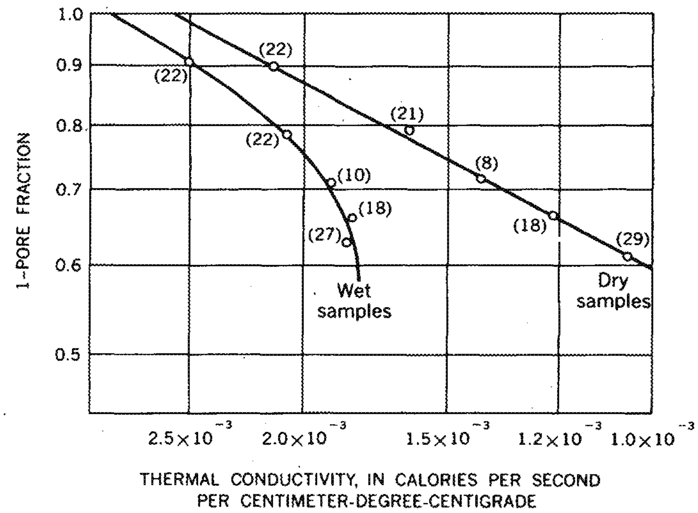

FIGURE 183.2.—Empirical correlation between average values of thermal conductivity and porosity for groups of tuff samples. The number of samples in each group is shown in parentheses.

ohm-meters, with a total range in measurements from 1.04 to 2.13 ohm-meters.

Interpretation of the in-place resistivity measurements on the basis of equation 3 shows that the tuff in the Oak Spring formation in the area of the underground tests is water-saturated at depths of more than 200 feet, but that fractures are not saturated, even at a depth of 900 feet.

SUMMARY

The amount of water in the rock was found to be the most important single factor in determining the physical properties of the tuff in Oak Spring formation. Variations in thermal conductivity, bulk density, enthalpy, and electrical properties of the tuff are all determined by the water content, directly or indirectly. Variations in strength and acoustic velocity are probably controlled by the fractures as well as by water content. The ability of the tuff to transmit fluids is probably more dependent upon fractures than upon permeability, because the permeability of unfractured samples is low.

ACKNOWLEDGMENTS

Much of the information in this report has been abstracted from unpublished reports by other Survey investigators. In particular, information about strengths was obtained from work by E. C. Robertson; about enthalpy, from F. C. Kracek; about acoustic velocities, from Louis Peselnick, and about mineralogy, from R. E. Wilcox.

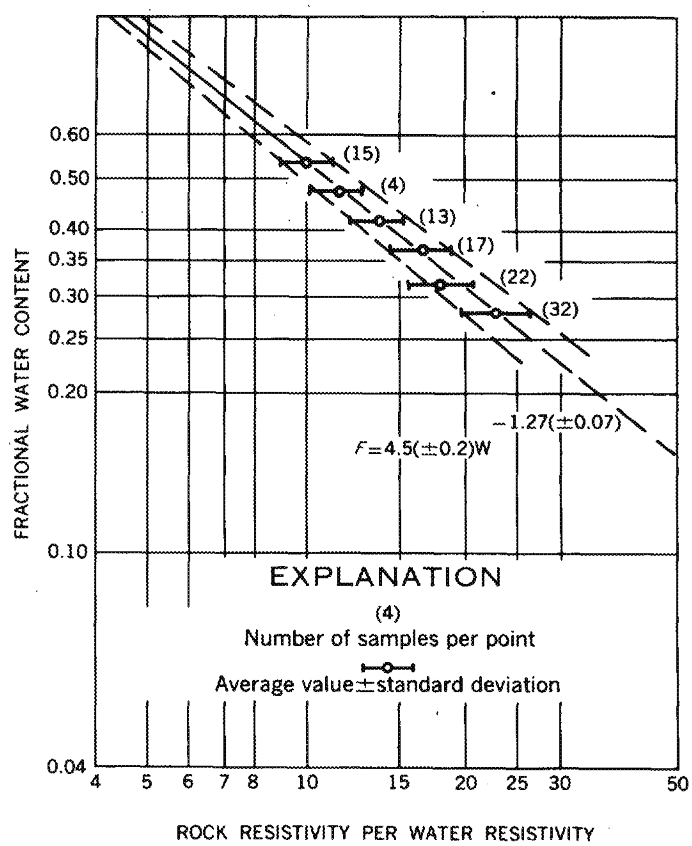

FIGURE 183.3—Correlation between average values of resistivity and porosity for samples of tuff.

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